Oxford Physics

UNIVERSITY OF OXFORD

A tunable source of quasi-phase-matched coherent EUV radiation

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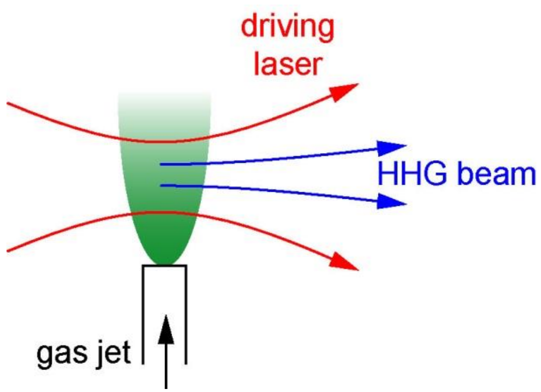
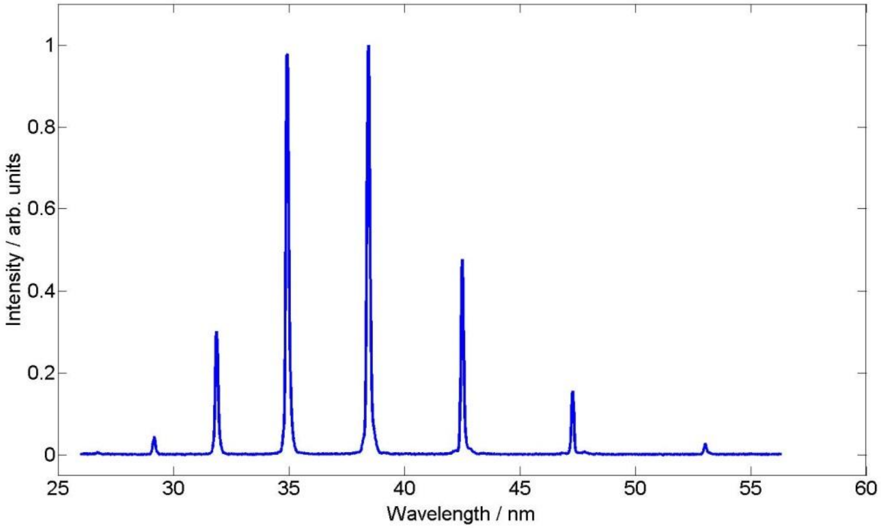
EPSRC Engineering and Physical Sciences Research Council

High harmonic generation



- Experimentally straight forward
- Focus ~ 1 mJ, 20-50 fs pulses into gas jet
- Peak intensity 10^{14} - 10^{15} W cm^{-2}



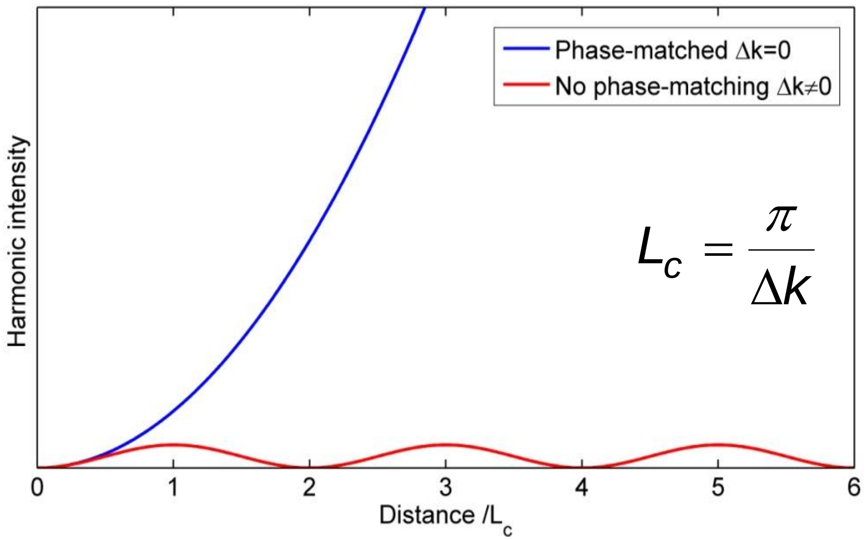
- HHG beam is coherent
- Odd harmonics with order *q* up to <u>few hundred</u>
- There is a well-defined cut-off frequency

$$\hbar\omega_{\text{cut-off}} = E_I + \beta I \lambda_0^2$$

Quasi-phase-matching

- HHG; coherent photons in excess of 1keV
- As in any nonlinear process, efficient harmonic generation requires

$$\Delta k = qk_{\omega 0} - k_{q\omega_0} = 0$$

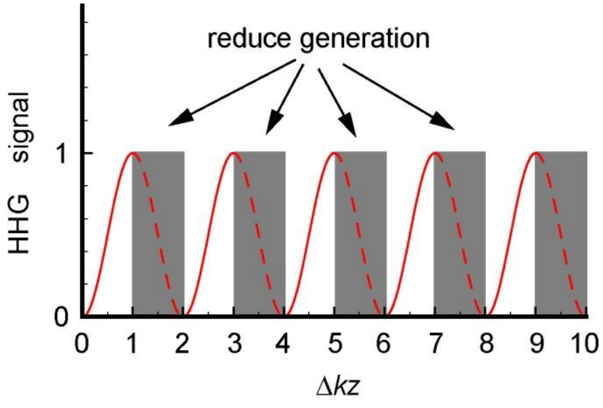


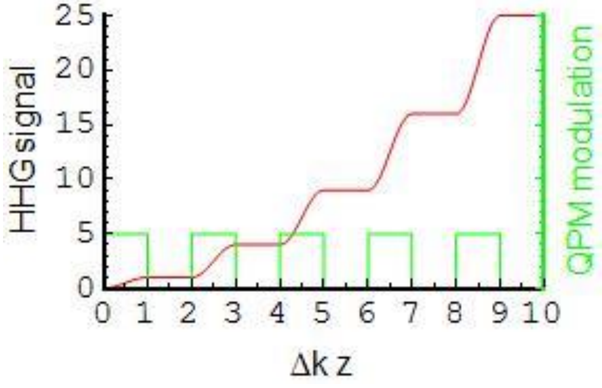
$$L_c = \frac{\pi}{\Delta k}$$

<u>Quasi-phase matching</u>

Modulate harmonic generation with period $L = 2mL_c$ $m = 1,2,3,\ldots$

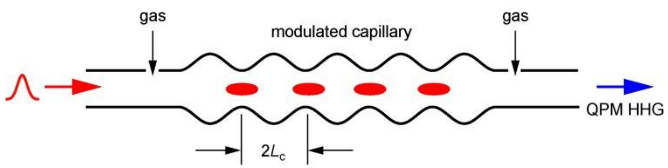
Harmonic output increases as N^2, where N is number of coherence lengths

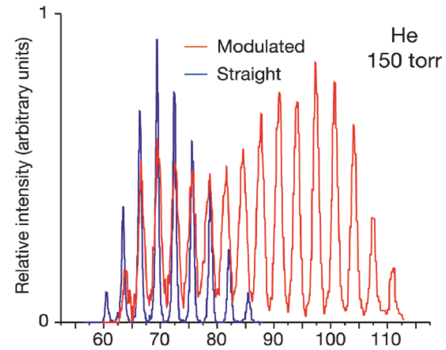




HHG QPM schemes

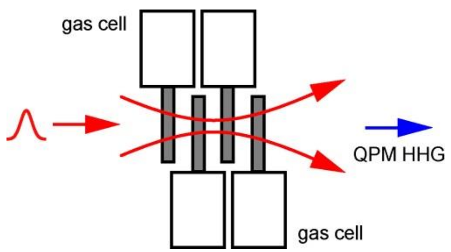
- Intensity modulation

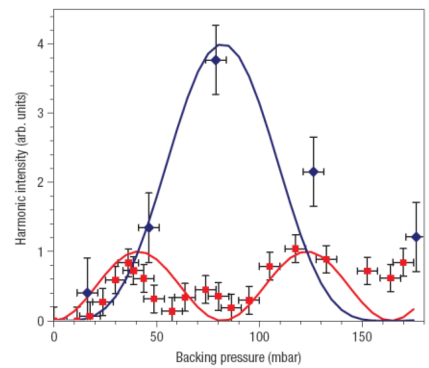




Paul et al. *Nature* **421** 51, (2003)

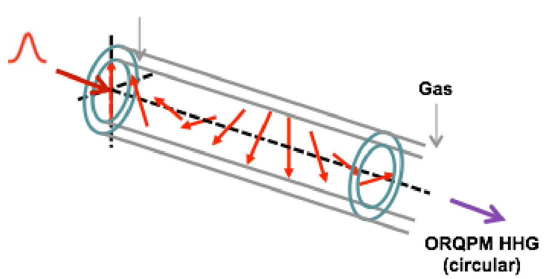
- Density modulation

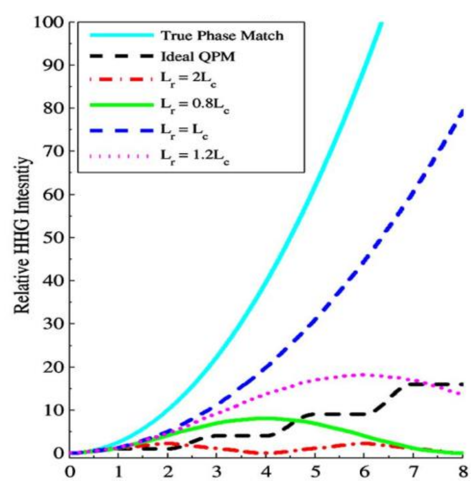




Seres et al. *Nature Physics* **3** 878, (2007)

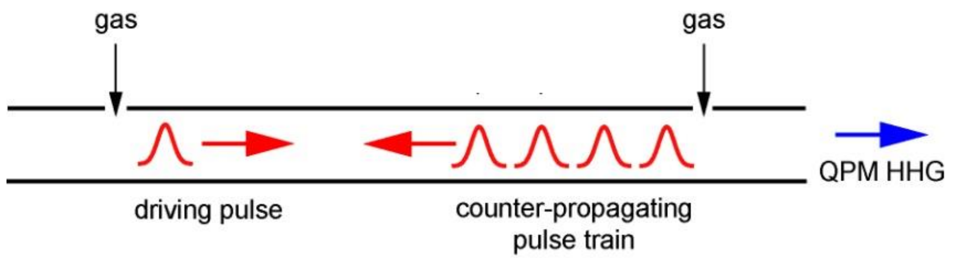
- Polarization modulation





Liu et al. *Opt. Letts*. **37** 2415, (2012)

Pulse train QPM

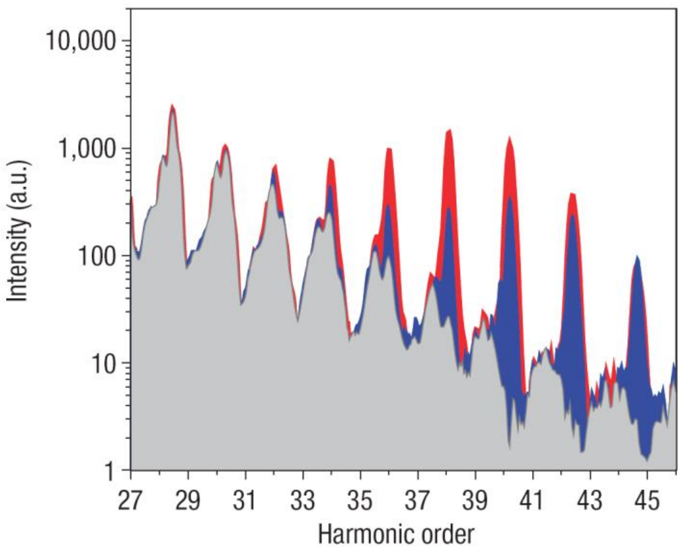


- HHG is suppressed in regions where the driving pulse overlaps with a counter-propagating pulse.

- QPM can be achieved by matching the pulse width and separation to the coherence length

<u>Experimental conditions</u>	
Capillary:	6 cm
Gas:	Ar, 7 Torr
Pulse train:	3 pulses, 0.1 mJ

Zhang et al. *Nature Physics* **3** 275 (2007)



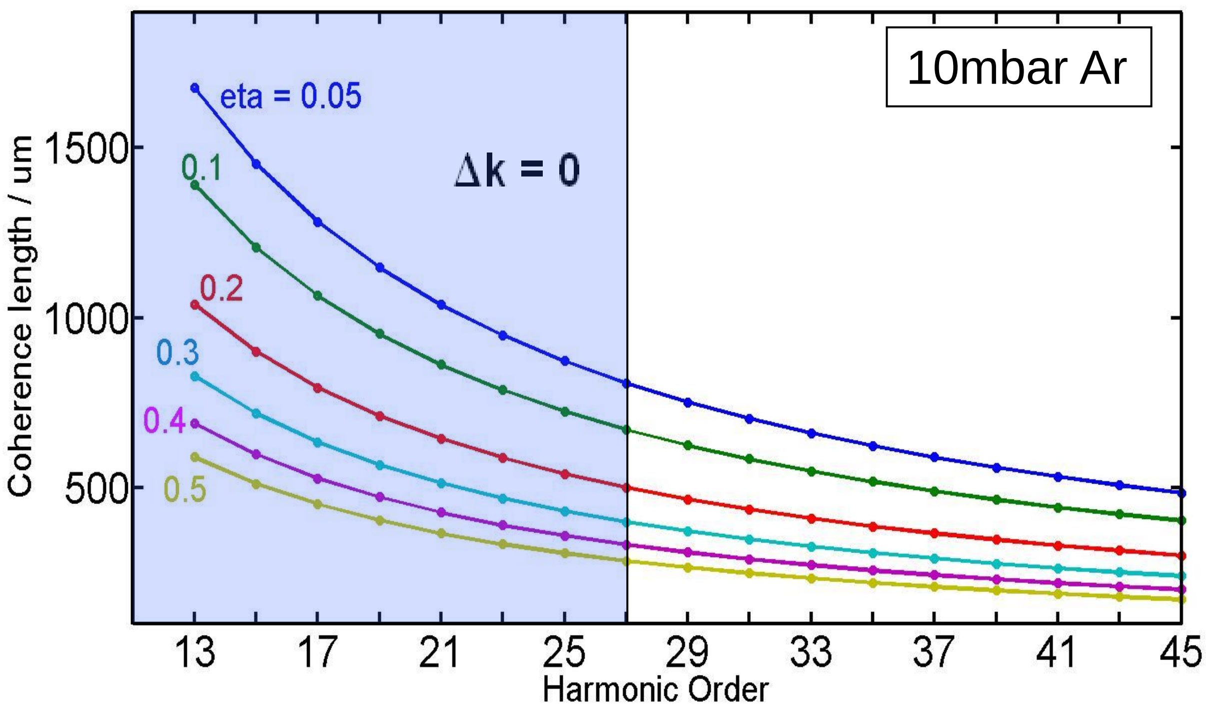
Matching pulses to coherence lengths

pressure

$$\Delta k = \Delta k_{\text{plasma}} + \Delta k_{\text{neutral}} + \Delta k_{\text{waveguide}}$$

$$= -\eta N_a r_e q \lambda_0 + \frac{2\pi q}{\lambda_0}\left[n(\lambda_0) - n(\lambda_0 / q)\right](1-\eta)\frac{P}{P_{\text{atm}}} - \frac{u_{n,m}^2 q \lambda_0}{4\pi a^2}$$

degree of
ionization

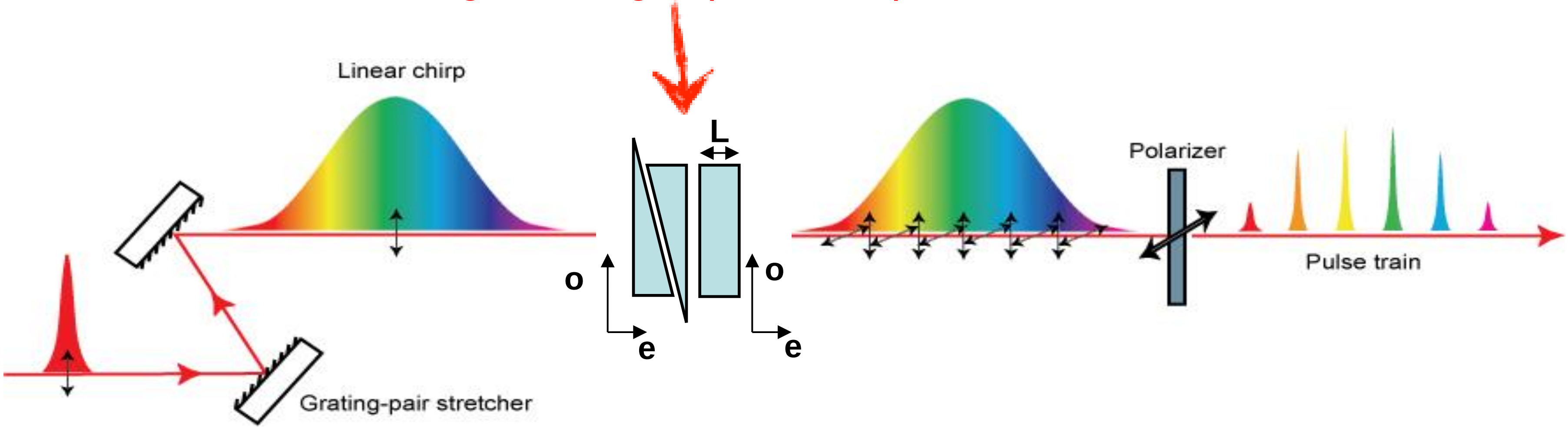


Ideal pulse trains:

- High energy
- High contrast
- Large number of pulses
- Easily tunable

Tunable pulsetrains

Birefringent wedges plus waveplate



Tunable pulsetrains

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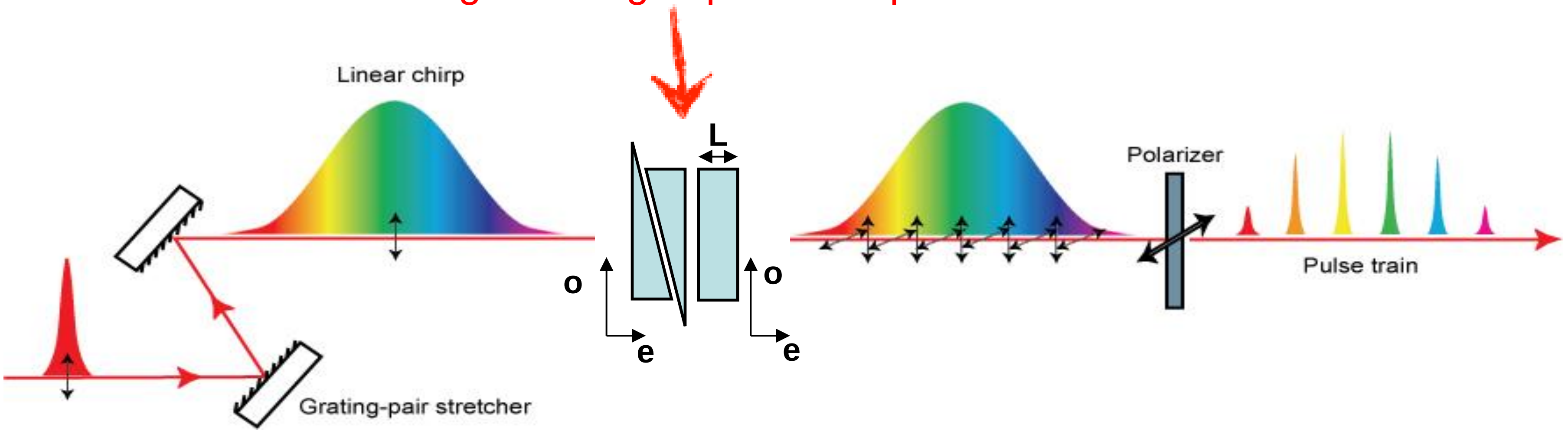
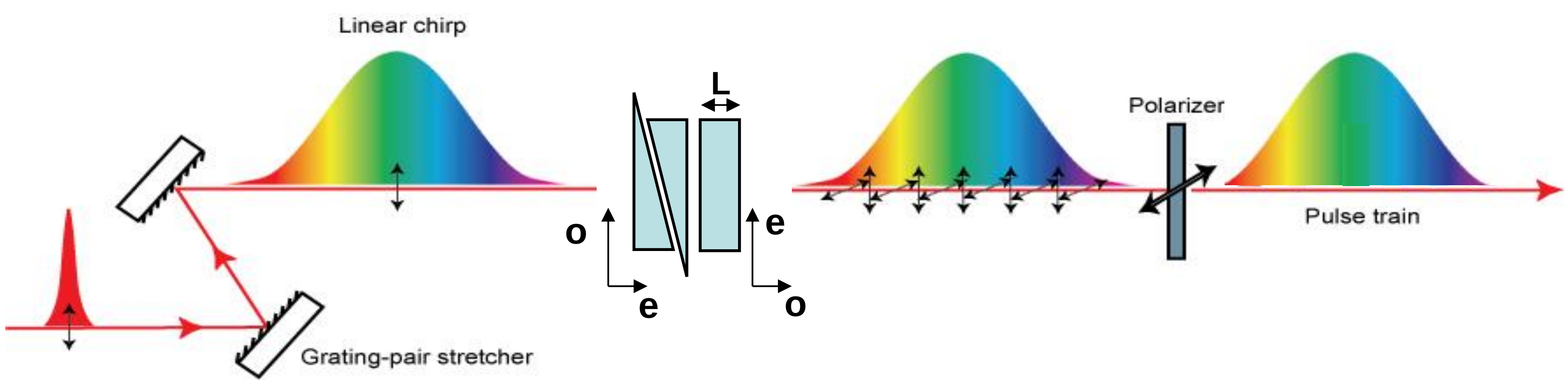
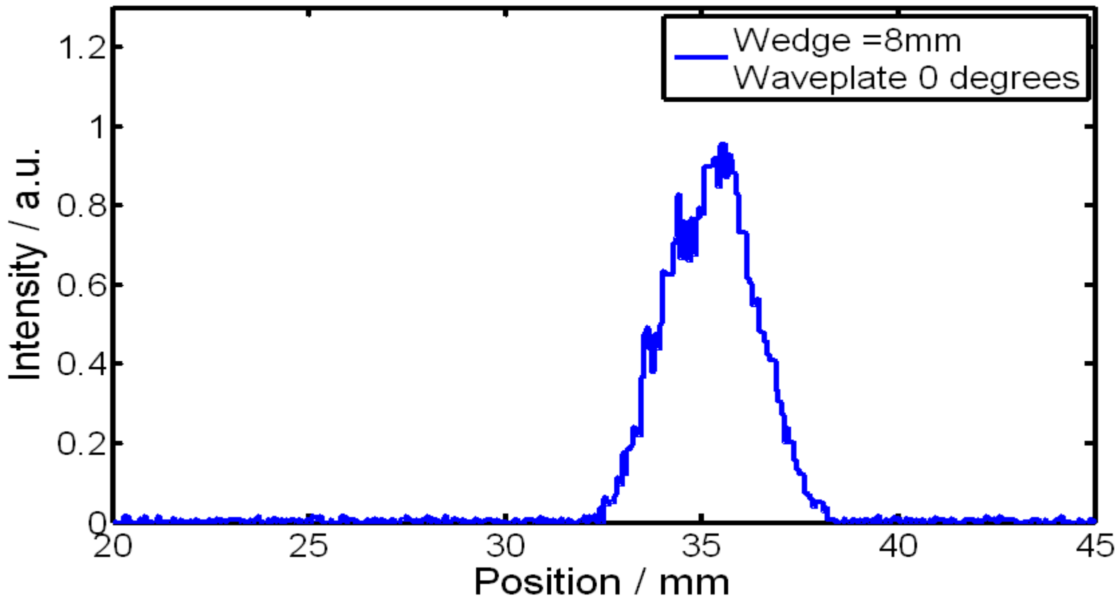
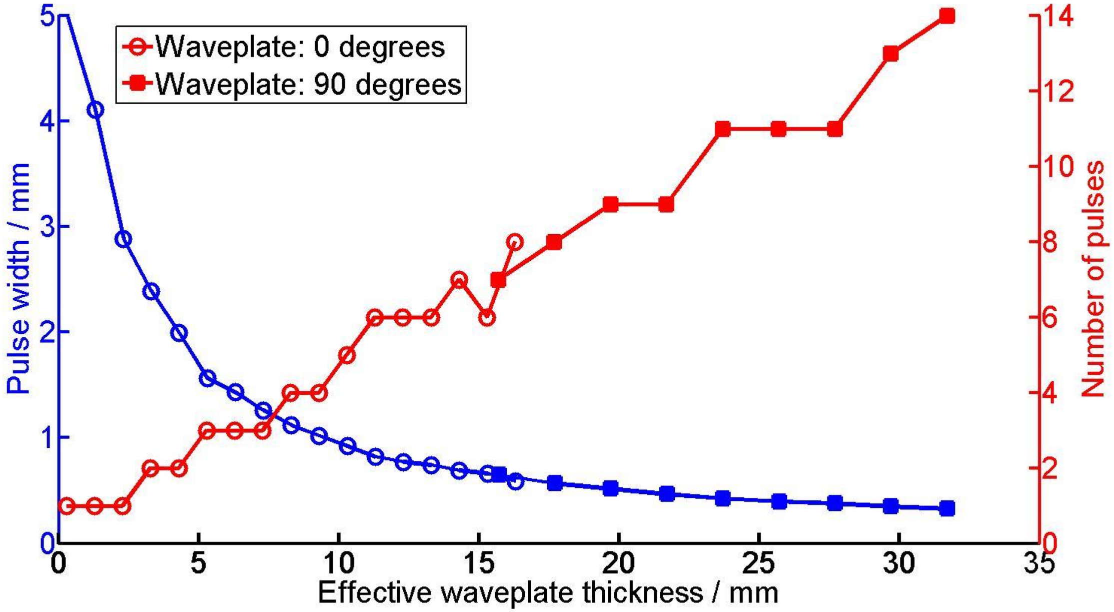




Vary effective thickness from 0 to 2L

Tunable pulsetrains





Cross-correlations of pulsetrain

830 lines/mm grating

14cm grating-retro separation

80% in first order

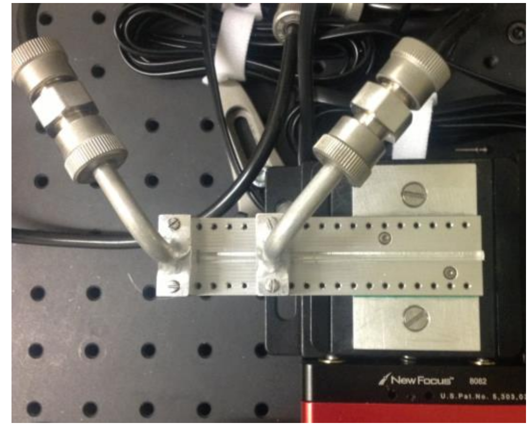
Waveplate: 8mm quartz
Wedges: 1 – 15mm quartz

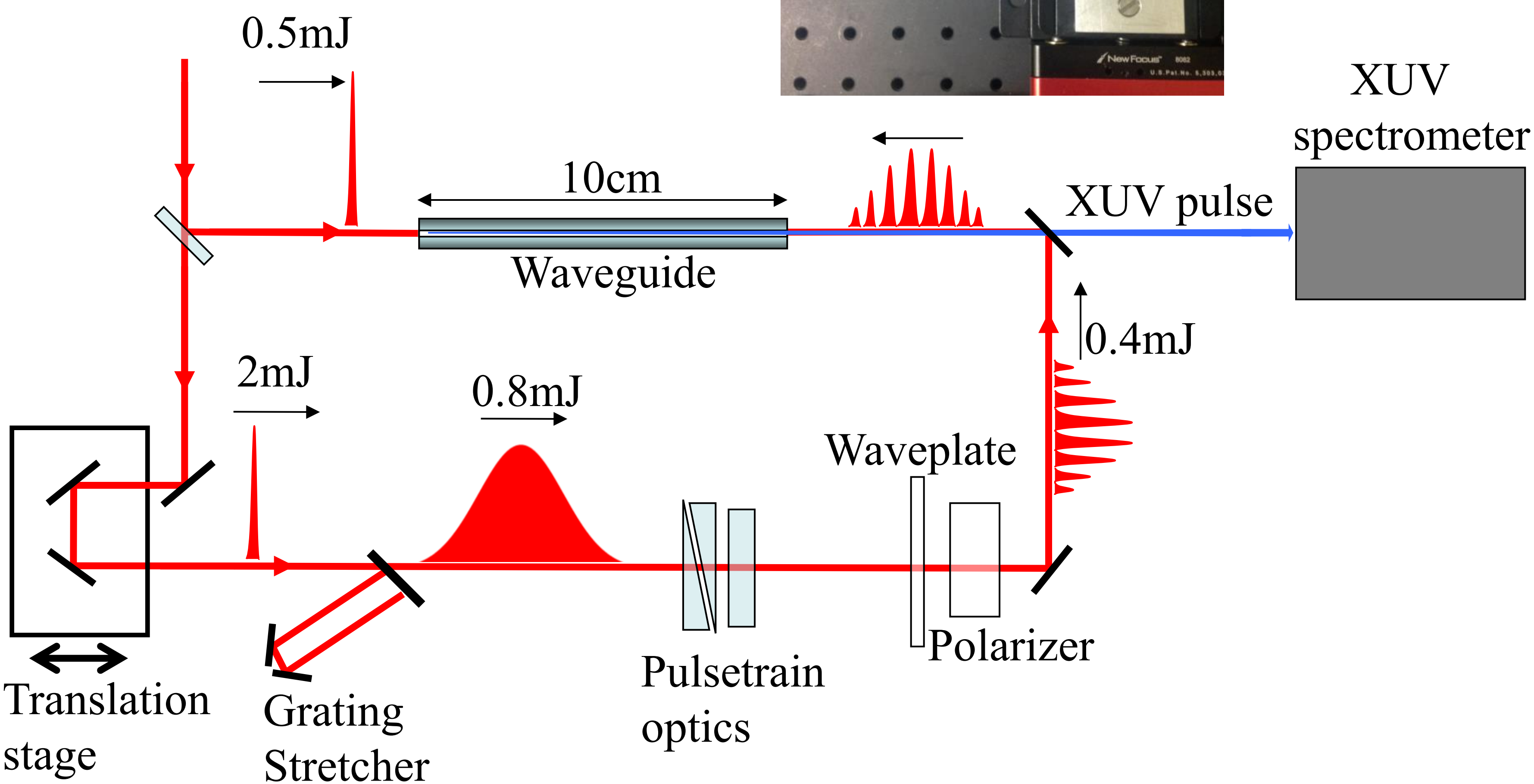
Pulse width ~ 1/L

Total stretch approx. constant

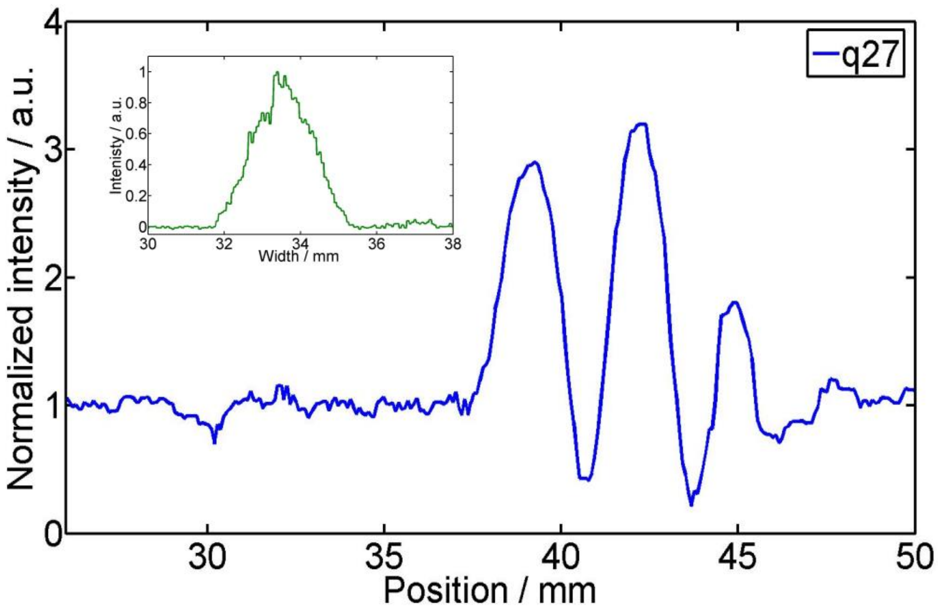
Pulsetrain experiment

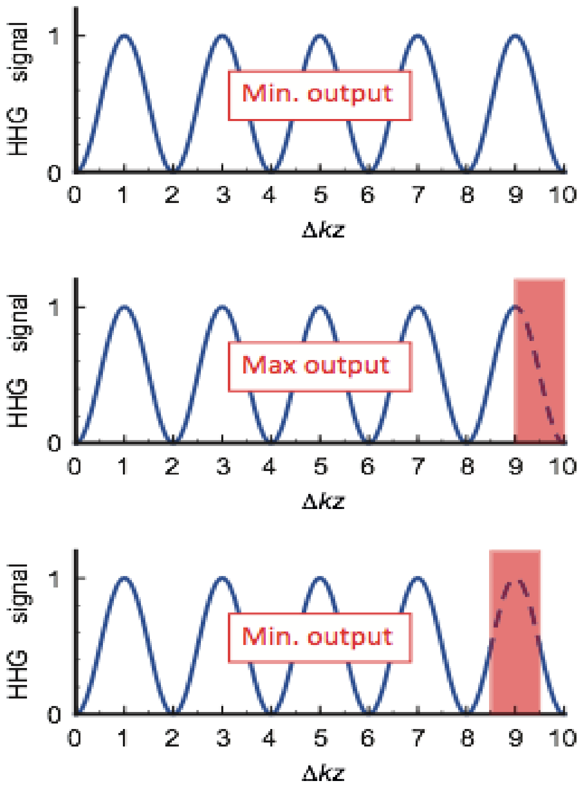
Laser:	35fs, 1kHz
Driver pulse:	0.5mJ
CP pulse:	2mJ
Gas:	14mbar Ar





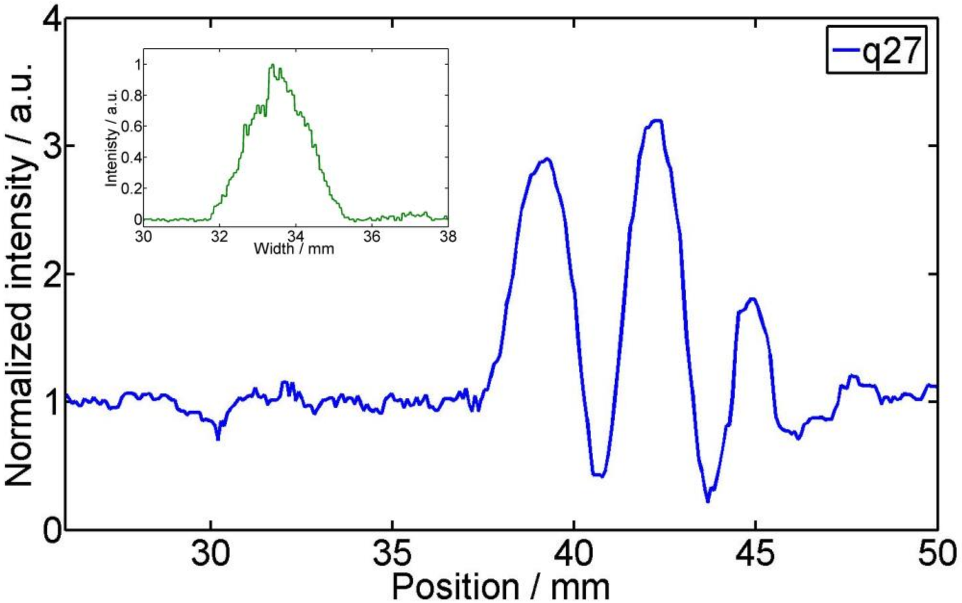
Results for single CP pulse

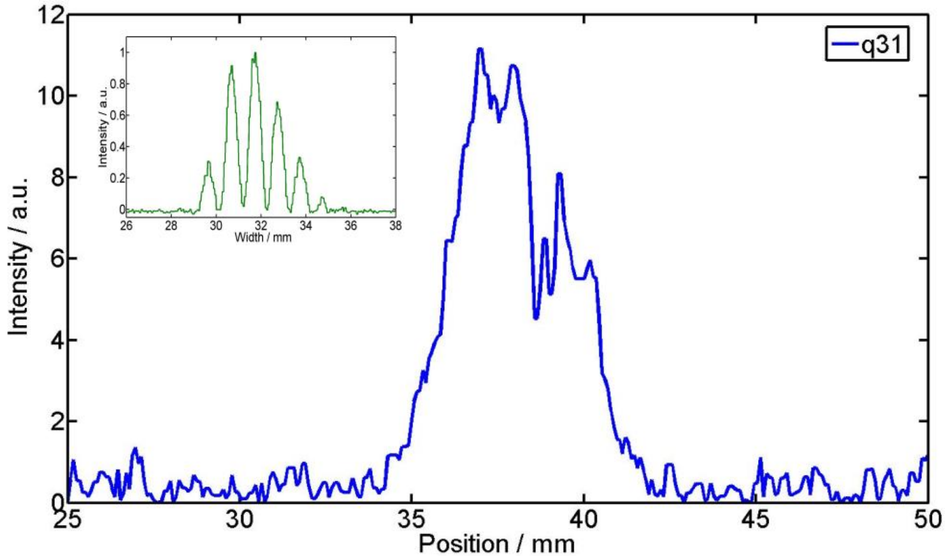


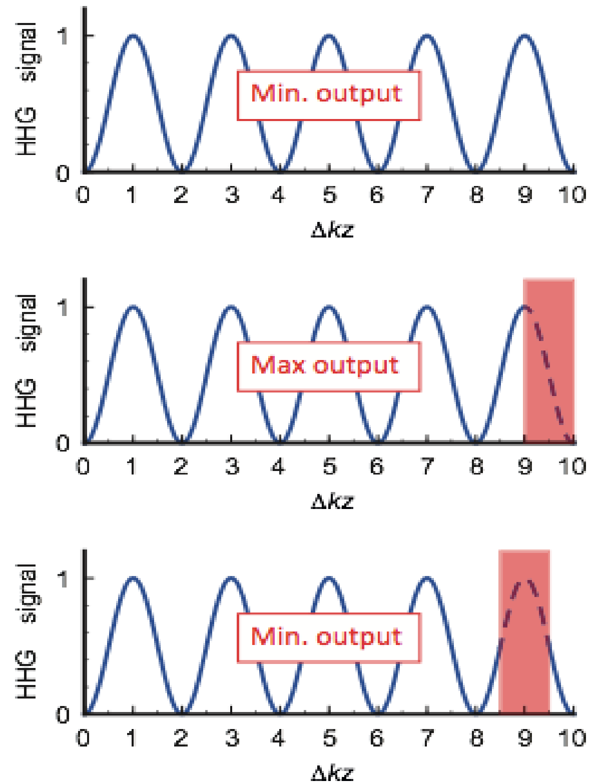


- Oscillations give coherence length
- *L*c decreases with increasing harmonic order
- Maximum enhancement occurs when $w = d = 2L_c$

Results for single CP pulse







- Oscillations give coherence length
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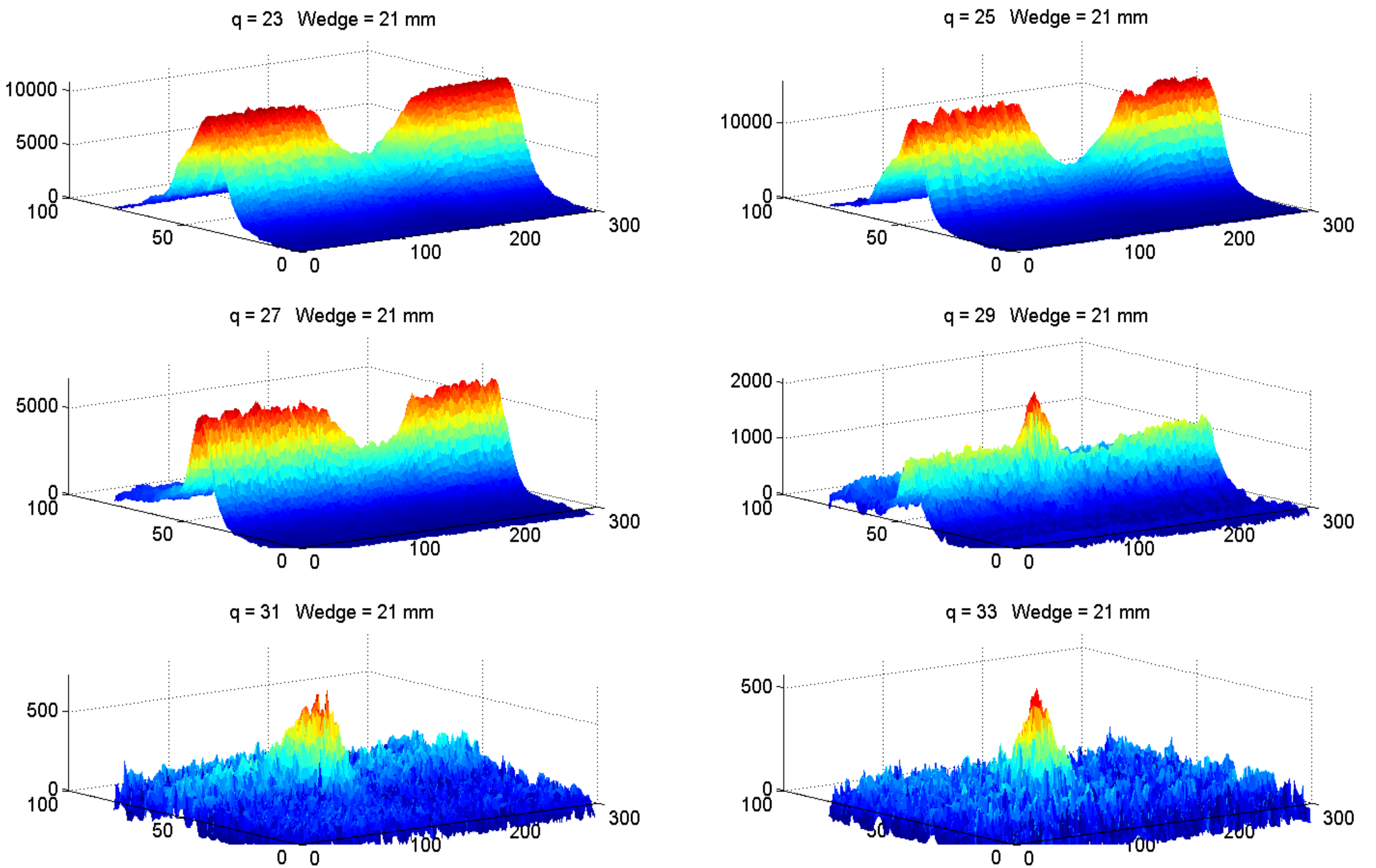
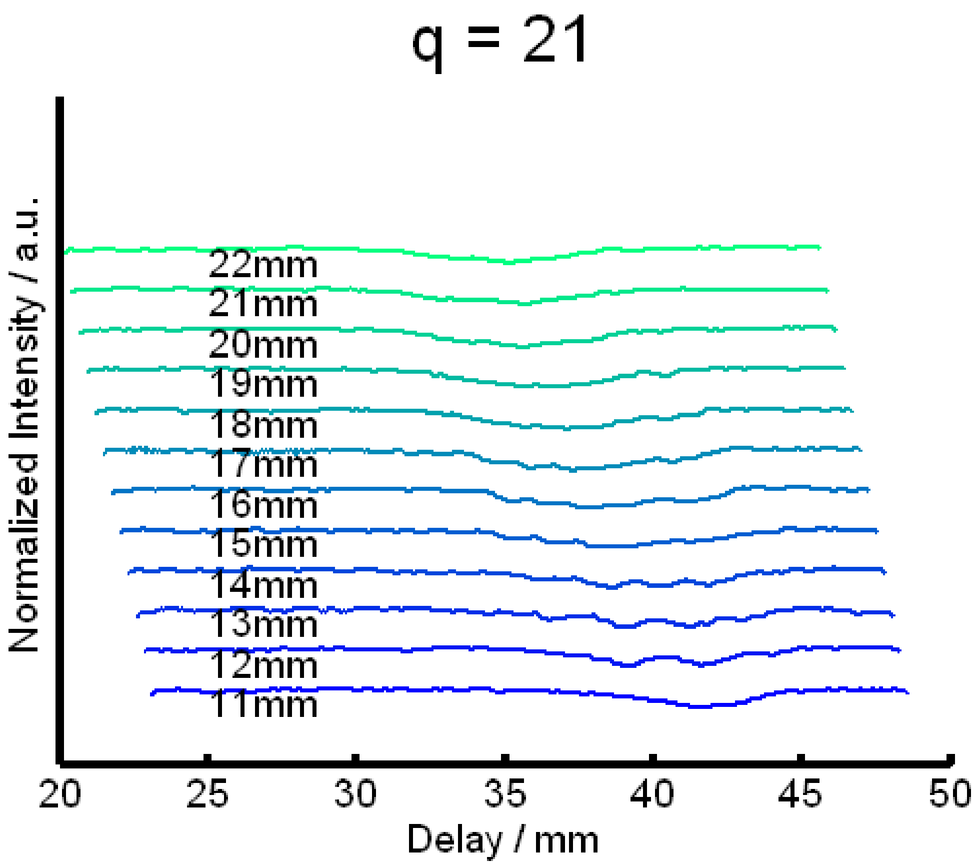
HHG data


q = 23 Wedge = 21 mm
q = 25 Wedge = 21 mm
q = 27 Wedge = 21 mm
q = 29 Wedge = 21 mm
q = 31 Wedge = 21 mm
q = 33 Wedge = 21 mm
10000
5000
2000
1000
500
0
100
50
200
300

HHG signal



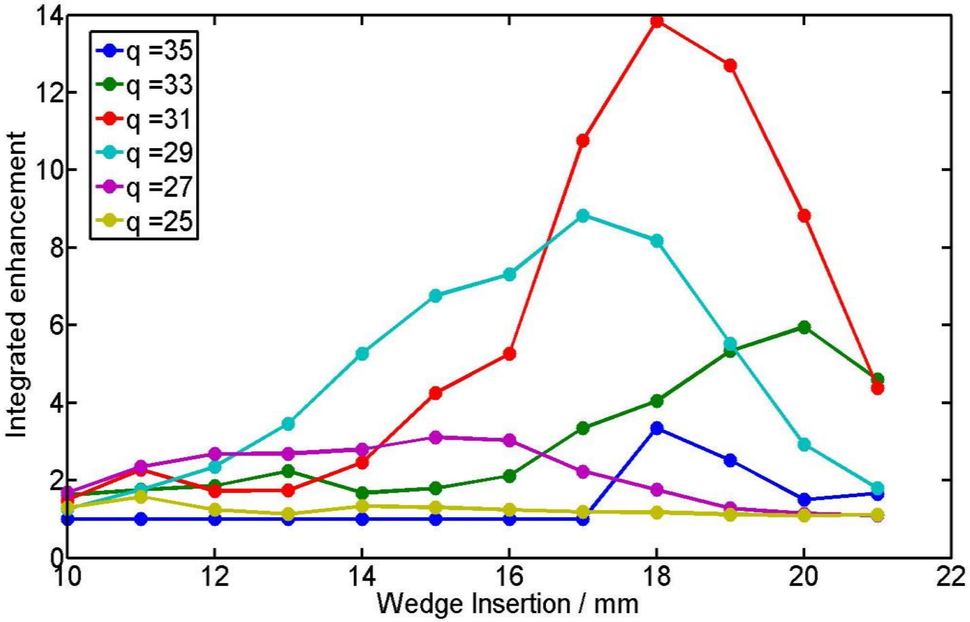
Low harmonic orders:

- suppression and coherent oscillations
- large pulse width

Higher harmonic orders:

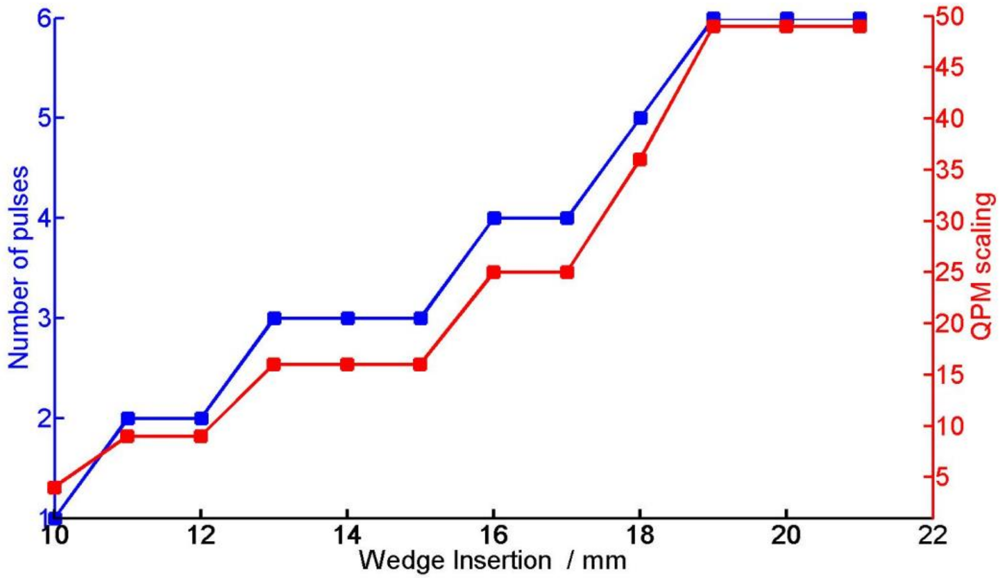
- enhanced signal due to QPM
- lower absorption
- more pulses in train
- enhancement until cutoff: q=35

Tunable enhancement



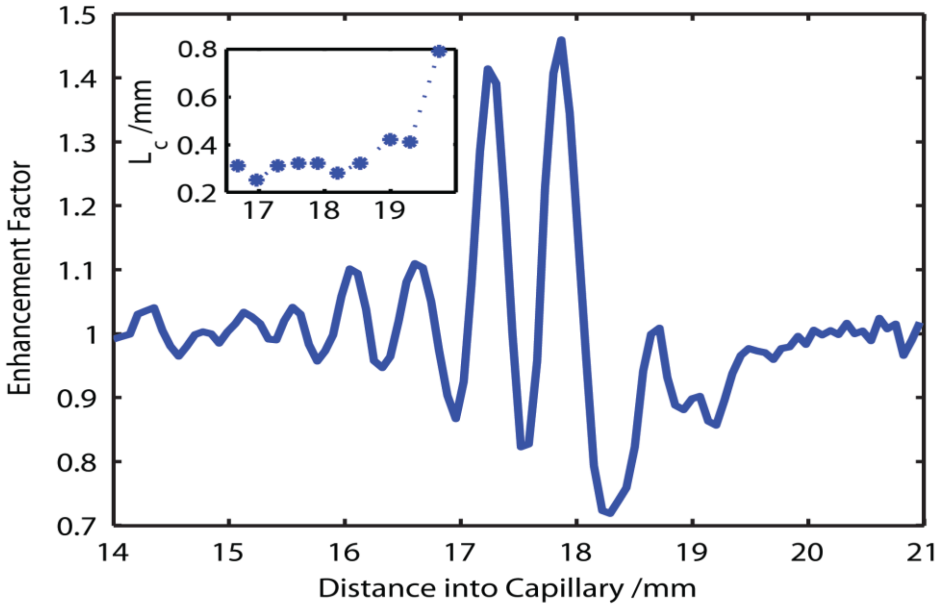
Normalized signal across 1nm window for each harmonic

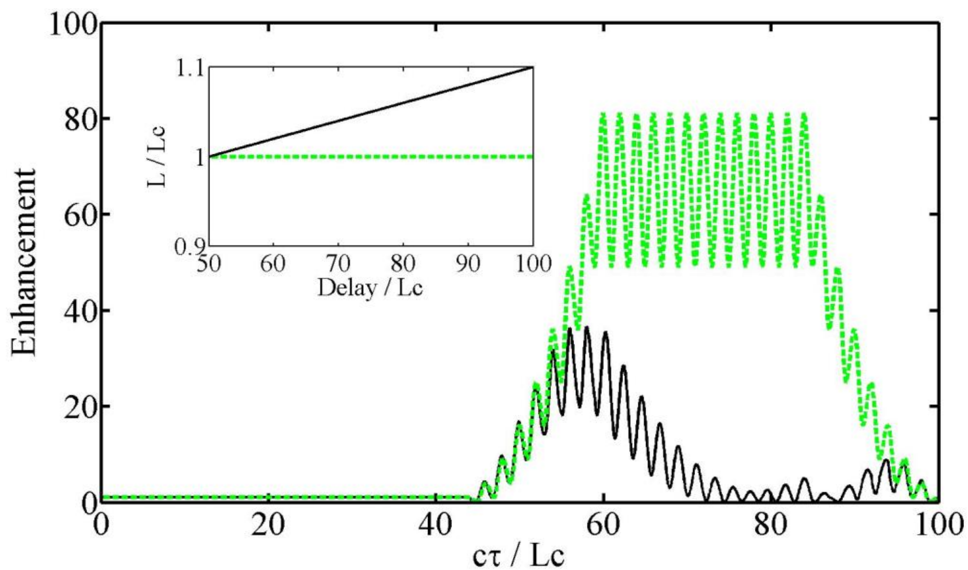
Estimated photon flux:
q31 (QPM): 1x10^7 photons/s



QPM intensity should scale as $(N+1)^2$

Variation of coherence length





Effects such as mode beating result in changes in the driver intensity

Coherence length varies as a function of position in the waveguide

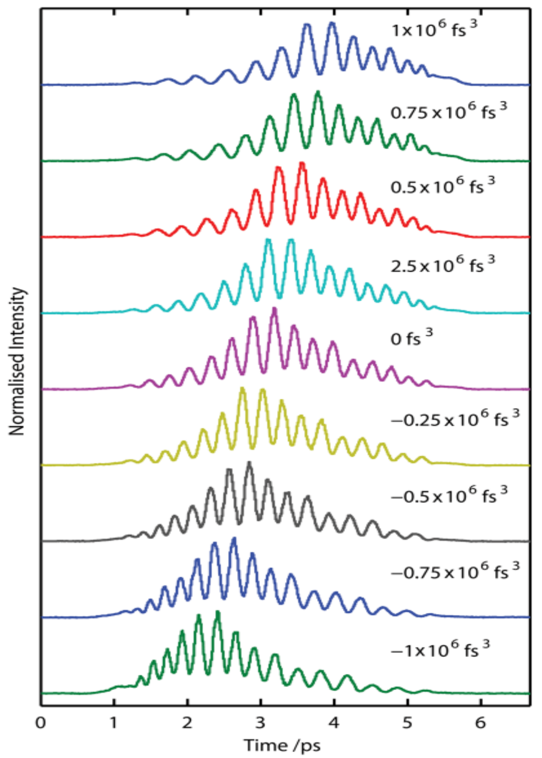
Need to control coherence length, or have more tuneable pulse trains.

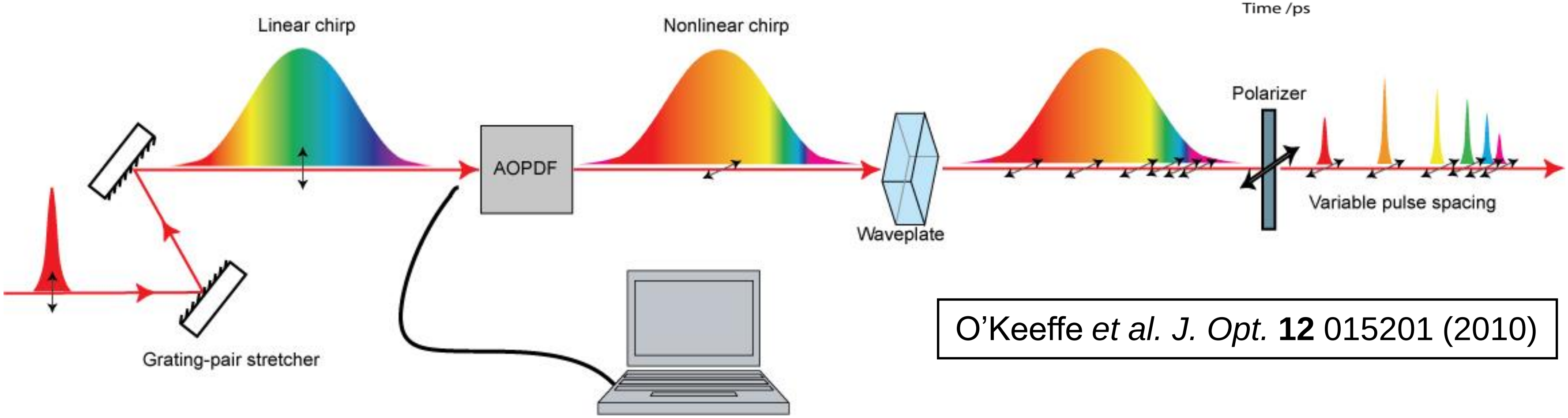
O'Keeffe *et al. Opt. Express.* **20** 6236, (2012)

Adaptive pulse trains

- Transmitted frequencies are evenly spaced: $\Delta\omega$
  - (neglecting GDD in wave plate and polarizer)
- Controlling dispersion controls when in stretched pulse transmitted frequencies occur
- Compensate for changing Lc

$$\Delta\tau_{\mathrm{p,p-1}} \propto p^{n-2}$$

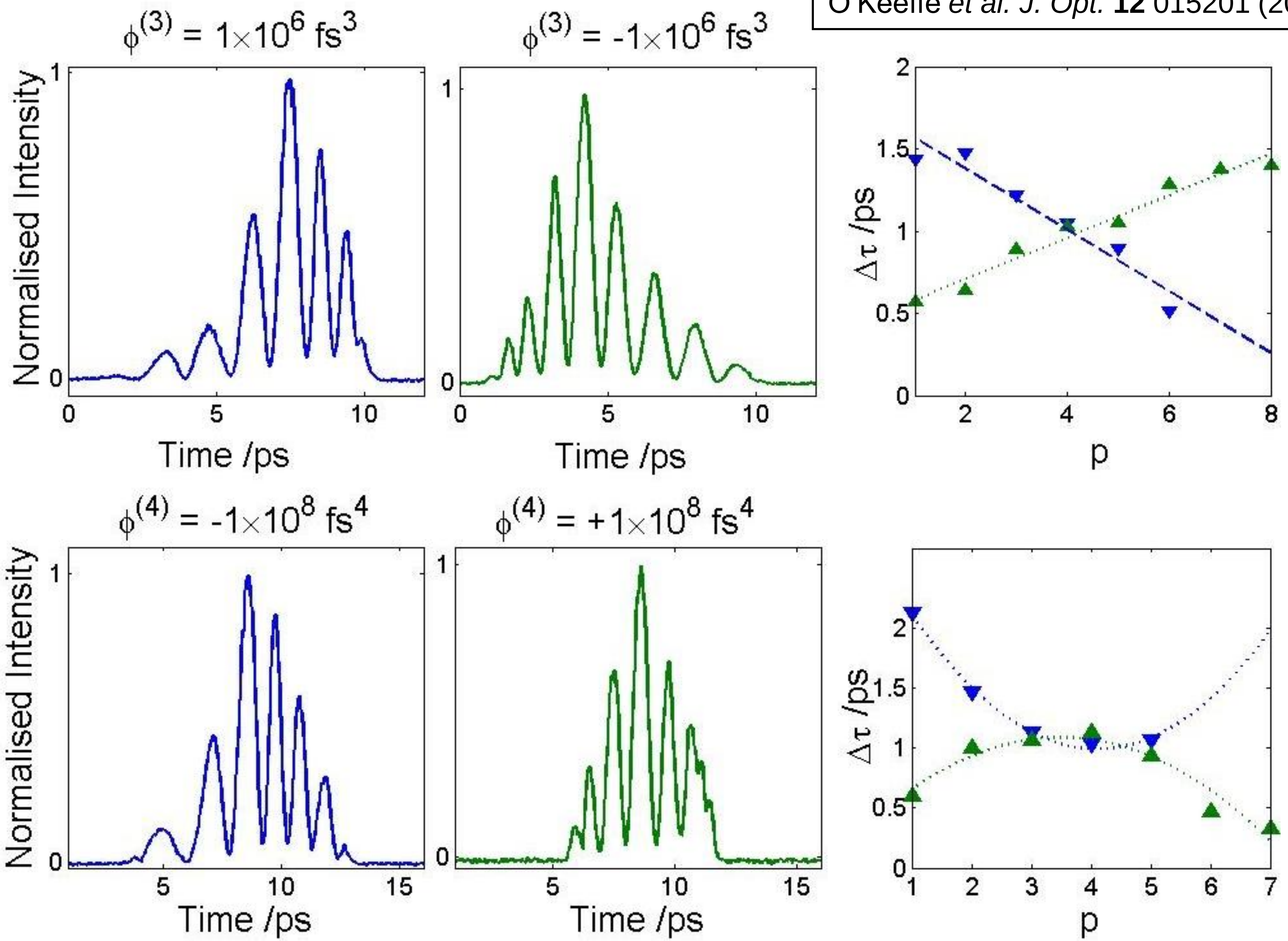




O'Keeffe *et al. J. Opt.* **12** 015201 (2010)

Adaptive pulse trains

O'Keeffe *et al. J. Opt.* **12** 015201 (2010)



Summary

- Simple technique for generating flexible pulse trains
- Tunable quasi-phase-matched HHG
- Programmable pulse trains to compensate for varying Lc

Future Work

- Extend tunable QPM to high orders – shorter driving pulses
- EPSRC grant in collaboration with Engineering Department at Oxford
  - HHG to investigate participate-strengthened alloys

Thank you

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